No. 115/20, 55–62
ISSN 2657-6988 (online)
ISSN 2657-5841 (printed)
DOI: 10.26408/115.06

Submitted: 14.09.2020
Accepted: 21.09.2020
Published: 30.09.2020

INFLUENCE OF VOLTAGE SUBHARMONICS ON INDUCTION MOTORS OF VARIOUS EFFICIENCY CLASSES

Marcin Pepliński

Gdynia Maritime University, Morska 81-87, 81-225 Gdynia, Poland,
Faculty of Electrical Engineering, Department of Marine Electrical Power Engineering,
ORCID 0000-0001-5952-1028, e-mail: m.peplinski@we.umg.edu.pl

Abstract: Power quality disturbances related to voltage waveform distortions and effective value deviation are common in power systems. Apart from higher harmonics, subharmonics and interharmonics may also appear in voltage waveforms. The presence of the above-mentioned disturbances causes additional power losses and an increase in thermal loads on induction motors. In this paper, the results of the study of the influence of subharmonics present in voltage waveform on the currents in the investigated induction motors of standard efficiency class – IE1 and high efficiency class – IE3, are presented.

Keywords: voltage quality, induction motor, subharmonics.

1. INTRODUCTION

Power quality disturbances such as: voltage waveform distortions, and deviations of the effective voltage value are common in power systems. Power quality disturbances have a detrimental effect on the operation of various elements of the power system, such as: transformer [Emanuel and Humi 2010] and electric power consumer. An induction motor is a consumer which is particularly sensitive to the quality of the supply voltage. Power quality disturbances cause additional power losses in such a motor, which result in an increase in the temperature of the windings [Gnaciński 2014; Gnaciński and Pepliński 2014]. As a consequence, in the motor a faster ageing of the insulation system takes place, resulting in a significant reduction in the lifetime of the machine [Gnaciński 2014; Gnaciński and Pepliński 2014].

The effects of supplying the motor with lowered quality voltage significantly depend on the characteristics of the motor [Gnaciński et al. 2020]. Currently, it is required that new motors have the efficiency class of at least IE3 (only exceptionally is class IE2 allowed, e.g. in the ready-to-use set of the motor driving the pump). At the same time, a significant number of motors with lower efficiency classes IE1 and IE2 are used. It should be mentioned that motors with different efficiency classes differ in some characteristics [Ferreira, Leprettre and de Almeida 2016], which may have an impact on the effects of lowered quality power supply.

Subharmonics are power quality disturbances that have a particularly detrimental effect on an induction motor. Subharmonics are components with frequencies lower than the frequency of the fundamental component. Subharmonics often occur together with voltage interharmonics, or disturbances with a frequency greater than the fundamental harmonic and not constituting its integer multiple.

The occurrence of subharmonic and interharmonic components in voltage waveforms has numerous reasons. One of them are non-linear loads, e.g. power inverters [Soltani et al. 2018] and receivers working with variable loads, e.g. induction furnaces [Sürgevil and Akpnar 2009]. A significant source of subharmonics and interharmonics can also be renewable energy sources such as wind farms [Djurović, Vilchis-Rodriguez and Smith 2015; Xie et al. 2017]. Subharmonics and interharmonics may arise here as a result of the variable rotational speed of the wind turbine and the air turbulence occurring when one of the wind turbine blades passes the tower [Kanellos and Hatziargyriou 2002].

In this paper, the results of experimental study of the influence of subharmonics present in voltage waveforms on the currents in the investigated induction motors of standard efficiency class – IE1 and high efficiency class – IE3, are presented.

2. TEST STAND

The test stand includes: a multi-machine system for subharmonics and interharmonics generation, two 3-phase induction motors (of high efficiency class – IE3 and standard efficiency class – IE1) and power quality analysers.

The multi-machine system used to generate the tested subharmonics consists of two salient-pole synchronous generators and a transformer. The generators are driven by induction motors powered by power inverters. One of the generators produces the fundamental voltage component, and the other the tested subharmonic. Both generators are connected by a 3-phase core-type transformer according to the diagram shown in Fig. 1 (from [Ho Fu 2001]). The objects of the study are two 4-pole squirrel-cage induction motors with a power of 3kW – a 3SIE100L4B-type motor (marked as A motor) and TSg100L-4B-type motor (marked as B motor). The differences between motors include their efficiency class – motor A is of IE3 class, and motor B – of IE1 class. The comparison of the parameters of both motors is presented in Table 1. The content of subharmonics in the supply voltage and current of the tested motors was measured using analysers – a power quality estimator and a PC-based power quality analyser. It is worth mentioning that the analyser – power quality estimator was designed in the Department of Marine Electrical Power Engineering at the Gdynia Maritime University and is certified by the Polish Register of Shipping.

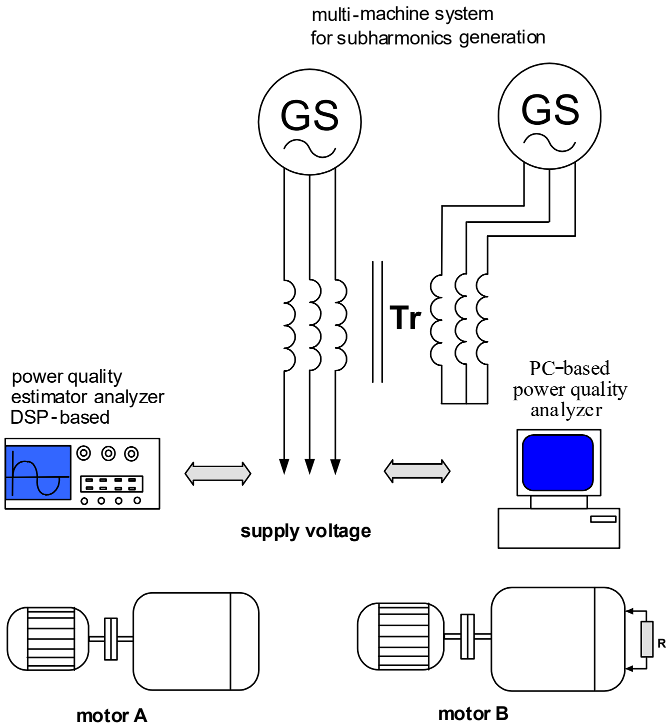

Fig. 1. A diagram of the test stand

Table 1. Rated parameters of the tested induction motors of TSg100L-4B- and 3SIE100L4B-type

Motor	Motor A	Motor B
Type	**3SIE100L4B**	**TSg100L-4B**
Efficiency class	**IE3**	**IE1**
Rated power [kW]	3.0	3.0
Rated frequency [Hz]	50	50
Rated voltage [V]	400	380
Rated current [A]	6.3	6.9
Rated rotational speed [RPM]	1465	1420
Rated power factor	0.79	0.81
Stator winding connections system	Y	Δ

3. RESULTS OF THE EXPERIMENTAL STUDY

This section presents the results of the experimental study of the influence of subharmonics with the sequence consistent with the currents in the windings of A and B induction motors. The relevant tests were performed for the load torque and the fundamental voltage harmonic with rated values and the amplitude of the tested subharmonics equal to 1% of the fundamental voltage component. Figure 2 shows an example of the current waveform in motor A for the tested subharmonic with the frequency $f_{sh} = 4$ Hz.

Figures 3 and 4 show the recorded spectra of the stator currents of motor A for the subharmonic with consistent sequence and the frequency $f_{sh} = 4$ Hz and $f_{sh} = 8$ Hz. In the discussed cases, the voltage subharmonic caused the flow of subharmonic currents with an amplitude equal to 22.4% I_1 and 22.2% I_1, respectively. Moreover, current subharmonics were accompanied by interharmonics with frequencies equal to 96 Hz (Fig. 3) and 92 Hz (Fig. 4) and amplitudes of 0.6% I_1 and 0.8% I_1, respectively.

Figures 5 and 6 show the recorded spectra of the stator currents of motor B for the subharmonic with consistent sequence and the frequency $f_{sh} = 4$ Hz and $f_{sh} = 8$ Hz. In the discussed cases, the voltage subharmonics caused the flow of subharmonic currents with an amplitude equal to 14.7% I_1 and 15.5% I_1, respectively. Moreover, current subharmonics were accompanied by interharmonics with frequencies equal to 96 Hz (Fig. 5) and 92 Hz (Fig. 6) and amplitudes of 0.9% I_1 and 1.0% I_1, respectively.

The presented test results show that subharmonics of low-frequency voltage cause the flow of current subharmonics in a much higher content in a high-efficiency motor than in a standard-efficiency motor. The main reason for this phenomenon is the fact that in motors of premium and high efficiency class, one of the methods of reducing power losses in the winding is to increase the cross-section of the stator winding wires in relation to the minimum derived from current density. The consequence of this is lower winding resistance. At the same time, for the tested subharmonics with frequencies $f_{sh} = 4$ Hz and $f_{sh} = 8$ Hz Hz, the winding resistance is also very low. Lowering the resistance influences the increase in the amplitudes of the currents caused by the discussed subharmonics occurring in the voltage. As a result, the corresponding subharmonics of the current are suppressed mainly by the winding resistance.

It should be mentioned that the subharmonics and interharmonics in the voltage and current waveforms can cause pulsation of electromagnetic torque and rotational speed as well as excessive vibrations in induction motors. Moreover, they increase the magnetising component of the current and power losses, leading to the saturation of the magnetic circuit and a decrease in the efficiency of the motor [Ghaseminezhad et al. 2017a; Ghaseminezhad et al. 2017b; Gnaciński and Pepliński 2017; Gnaciński, Pepliński and Hallmann 2019]. For example, in the study [Gnaciński, Pepliński and

Hallmann 2019], it was demonstrated that for the tested motor A, the contents of subharmonics with an amplitude of 1% U_n cause vibrations with amplitudes significantly exceeding the long-term permissible levels of vibration amplitudes specified in the standards for electric machines [ISO Standard 20816-1 2016]. In addition, for the tested motor A, according to the analysis contained in [Gnaciński, Pepliński and Hallmann 2019], at idle speed, the levels of long-term permissible vibrations were exceeded for the subharmonic amplitude as low as of 0.2% U_n.

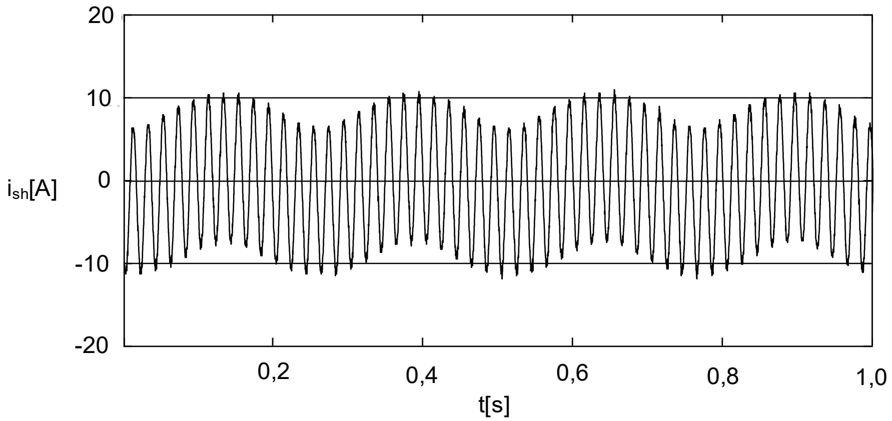

Fig. 2. The measured waveform of the current consumed by motor A for the supply voltage containing the subharmonic of consistent sequence, frequency f_{sh} = 4 Hz and amplitude equal to u_{sh} = 1% of the amplitude of the fundamental harmonic

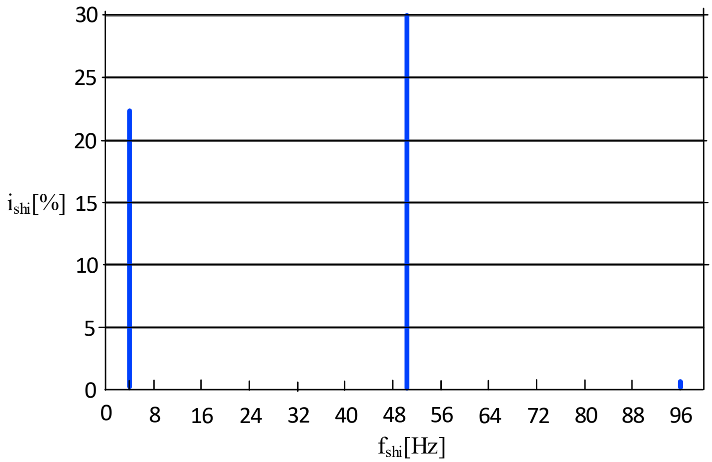

Fig. 3. The spectrum of the current consumed by motor A for the supply voltage containing the subharmonic of consistent sequence, frequency f_{sh} = 4 Hz and amplitude equal to u_{sh} = 1% of the amplitude of the fundamental harmonic (the current waveform is shown in Fig. 2)

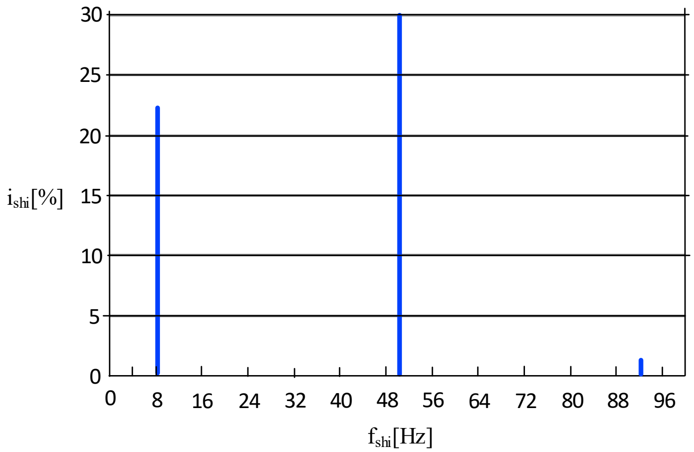

Fig. 4. The spectrum of the current consumed by motor A for the supply voltage containing the subharmonic of consistent sequence, frequency f_{sh} = 8 Hz and amplitude equal to u_{sh} = 1% of the amplitude of the fundamental harmonic

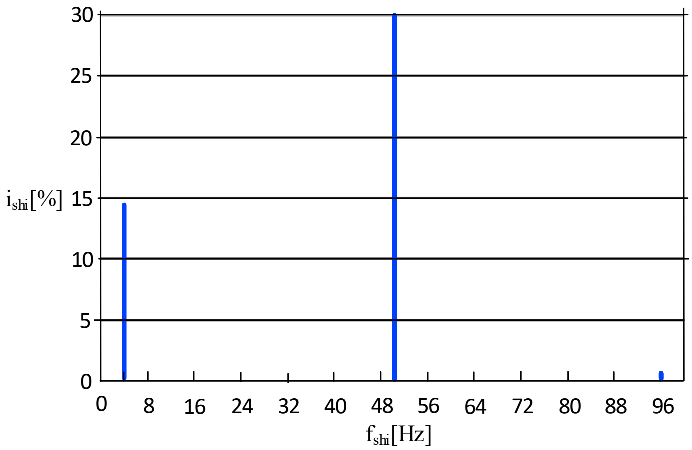

Fig. 5. The spectrum of the measured current consumed by motor B for the supply voltage containing the subharmonic of consistent sequence, frequency f_{sh} = 4 Hz and amplitude equal to u_{sh} = 1% of the amplitude of the fundamental harmonic

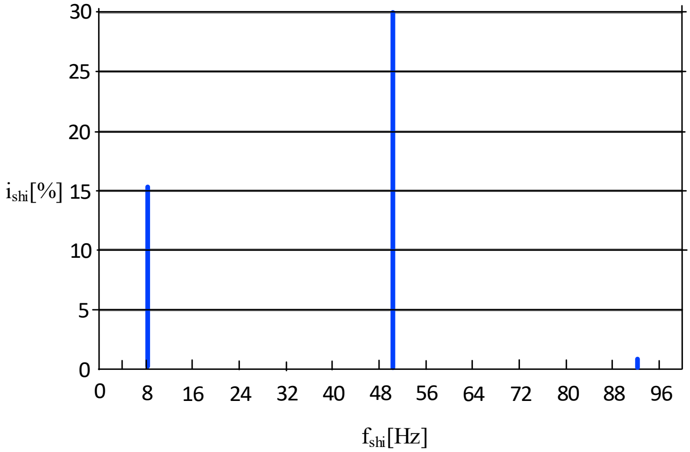

Fig. 6. The spectrum of the measured current consumed by motor B for the supply voltage containing the subharmonic of consistent sequence, frequency f_{sh} = 8 Hz and amplitude equal to u_{sh} = 1% of the amplitude of the fundamental harmonic

4. CONCLUSIONS

The presented test results show that subharmonics of low-frequency voltage (f_{sh} = 4 Hz and f_{sh} = 8 Hz) cause the flow of current subharmonics of much higher values in a IE3-efficiency class motor than in a IE1-efficiency class motor. Higher subharmonics of the current favour other unfavourable phenomena, such as an increase in power losses, torque pulsations and vibrations [Gnaciński et al. 2019a,b]. It should be emphasised that for the tested motor of the IE3 efficiency class, even voltage subharmonics with an apparently negligible amplitude amounting to only 0.2% of the fundamental voltage component can cause excessive vibrations [Gnaciński et al. 2019a,b].

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